

Lightweight panels based on Helmholtz resonators for low-frequency acoustic insulation

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Abstract. In this study, we propose a novel lightweight acoustic metamaterial panel composed of coupled Helmholtz resonators, designed to insulate low-frequency broadband noises effectively. Through finite element analysis, we observe the emergence of band gaps with varying widths, depending on the unit cell dimensions, the band gaps start at 100 Hz, and as the scale decreases, the band gaps shift to higher frequencies within specific ranges. These band gaps arise from the coupling of two Helmholtz resonators with different volumes but a common neck. For our work, we use ABS materials, which facilitate easy panel manufacturing. Moreover, we also explored the potential of other materials to enhance the low-frequency broadband sound insulation performance of the system. The results obtained from this research provide promising insights into developing lightweight panels for efficient low-frequency broadband sound insulation.

1 Introduction

In recent years, the demand for effective acoustic insulation solutions has intensified, driven by growing concerns over noise pollution and the requirement to create quieter living and working environments [1]. The development of metamaterials has emerged as a promising avenue to achieve unprecedented control over acoustic wave propagation [2, 3]. These innovative materials, engineered with complex structures and properties not found in nature, exhibit extraordinary capabilities in manipulating sound waves with exceptional precision with both local resonance and Bragg scattering [4]. Many types of resonators have been used in noise reduction, such as Membranes [5], space coiled [6], Fabry-Perot structures [7], quarter-wavelength resonators [8], and Helmholtz resonators [9].

The Helmholtz resonator is a highly classic acoustic system that has been widely explored for decades. Helmholtz resonators have been broadly used in creating acoustic metamaterials for noise attenuation in recent years, with the development of energy harvesting and metamaterials research [10]. Most researchers have attempted to investigate the concepts of low-frequency sound attenuation using Helmholtz resonators. Yamamoto (2018) suggested a Helmholtz resonator embedded in a vibrating plate that works similarly to elastic membranes at the surface of a planar construction, which differs from the usual Helmholtz

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resonator [11]. Furthermore, Ahmad Yusuf Ismail *et al.* (2022) investigated the use of a Helmholtz resonator-based acoustic metasurface to improve sound transmission loss performance. The metasurface is made up of periodic cells of Helmholtz resonators that are designed to refract sound waves in desired directions with minimal energy loss. Thus, parametric studies explored the sensitivity of design variables, and experimental validation demonstrated the effectiveness of their metasurface design [12]. In other research conducted in 2022, F. Langfeldt *et al.* studied plate-type acoustic metamaterials. These metamaterials are comprised of a thin film with periodically incorporated masses. They proposed incorporating Helmholtz resonators to improve the bandwidth of plate-type acoustic metamaterials. The metamaterial provides improved sound transmission loss over a wider frequency range by introducing more peaks in the transmission loss spectrum, making it more adaptable and suitable for a variety of applications [13]. In addition, Alexandru Crivoi *et al.* (2022) investigated a multi-layer sound attenuating metamaterial with ventilation capability by adding arrays of Helmholtz resonators implanted in walls. This innovative metamaterial is specifically designed to enhance sound attenuation within the audible range from 300 to 2000 Hz while maintaining effective ventilation. To assess the performance of the barriers and verify the efficacy of the proposed design, they employed a comprehensive approach, utilizing analytical, numerical, and experimental methods [14].

One particular class of metamaterials that has garnered significant interest in acoustic engineering is lightweight metamaterials [5, 15]. The utilization of lightweight materials in acoustic insulation presents numerous advantages, including enhanced portability, cost efficiency, and reduced environmental impact.

In this article, we present a novel lightweight acoustic metamaterial design for sound attenuation by leveraging the coupling of Helmholtz resonators. Employing the finite element method, we conduct a comprehensive investigation encompassing multiple aspects. Firstly, we calculate the sound dispersion characteristics for the proposed design, allowing us to gain valuable insights into its acoustic behavior. Subsequently, we delve into the transmission properties of the design, thoroughly assessing its ability to mitigate sound propagation. Moreover, our study extends to the influence of the cell scale on the emergence of band gaps, which play a crucial role in sound insulation efficacy. Through a systematic examination of these factors, we aim to elucidate the potential of our proposed design as an efficient and versatile approach for noise control, opening new horizons in acoustic engineering and contributing to quieter and more compatible environments.

2 Methods and models

2.1 Design of the lightweight panel

The design of the lightweight acoustic metamaterial panel is showcased in Figure 1, where the left side (Figure 1(a)) illustrates the configuration of the panel, while the right side (Figure 1(b)) depicts the unit cell along with its corresponding geometrical parameters. The fundamental concept underlying this design revolves around the integration of a coupled Helmholtz resonator system consisting of two resonators with distinct volumes but sharing a common neck. This design allows for the creation of a highly effective and lightweight acoustic metamaterial capable of trapping sound waves with high coefficients of reflection or absorption while also achieving great noise-reducing properties. Through a thorough examination of the structure's acoustic behavior and geometric dimensions, the groundwork is laid for further investigation and development of advanced lightweight acoustic insulation panels, promising a low-cost material for noise mitigation across a wide range of applications and industries. The panel is built on the material Acrylonitrile Butadiene Styrene (ABS),

which has the following mechanical properties: a Young's modulus $E = 2.6$ GPa, a density $\rho = 1080$ kg/m³, and a Poisson's ratio $\nu = 0.4$.

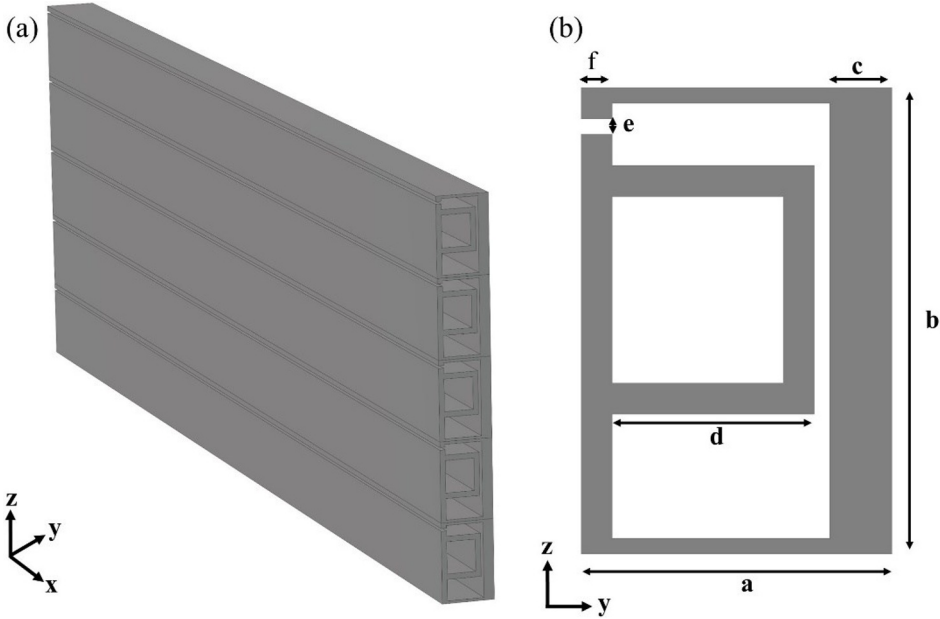


Fig. 1. Scheme of acoustic metamaterials panel. (a) Conceptual view of the acoustic panel. (b) Scheme of the unit cell with the geometrical parameters $a = 2$ cm, $b = 3a/2$ cm, $c = a/5$ cm, $d = 13a/20$ cm, $e = a/20$ cm, and $f = a/10$ cm.

2.2 Numerical modeling

To ascertain the acoustic behavior of the presented unit cell, our investigation proceeds in two crucial steps. Initially, we delve into the dispersion analysis, where we determine the eigenvalues within the first irreducible Brillouin zone (ΓX). This fundamental study provides crucial insights into the propagation characteristics of sound waves within the unit cell. The wave propagation in both air and solids is governed by both equations: sound waves in air (Eq. 1) for the differential pressure $\mathbf{p}$ and the propagation in solids, which is governed by the weak formalism of the time-harmonic Navier equation (Eq. 2).

$$\nabla \cdot \left(\frac{1}{\rho_{air}} \nabla \mathbf{p} \right) + \frac{\omega^2}{\rho_{air} C^2} \mathbf{p} = 0, \quad (1)$$

$$\frac{E}{2(1+\nu)} \left[\frac{1}{(1-2\nu)} \nabla (\nabla \cdot \mathbf{u}) + \nabla^2 \mathbf{u} \right] = -\omega^2 \rho_s \mathbf{u}, \quad (2)$$

where $\mathbf{p}$ is the acoustic pressure, $\mathbf{u}$ is the displacement vector, $\rho_{air} = 1.21$ kg/m³ and ρ_s are the densities of the air and solid, respectively. $C = 343$ m/s is the sound speed in the air, ω is the angular frequency of the acoustic wave, E is the Young's modulus, and ν is the Poisson's ratio.

To calculate the dispersion curve, we considered that the panel is infinite in the y -direction, and in the x -direction the Floquet-Bloch conditions are applied as follows:

$$\mathbf{u}(a + x) = \mathbf{u}(x) e^{ika}, \quad \mathbf{p}(a + x) = \mathbf{p}(x) e^{ika}. \quad (3)$$

From the Eq. 1, Eq. 2 and Eq. 3, we deduce the following eigenfrequency equation:

$$[K(k) - M(k) \omega^2]A = 0, \quad (4)$$

where A represents $\mathbf{u}$ and $\mathbf{p}$, $M(k)$ and $K(k)$ represent the mass and stiffness matrices, respectively, which depend on the reduced wavenumber k . For a given value of k , there is an eigenfrequency from which the dispersion relation can be derived.

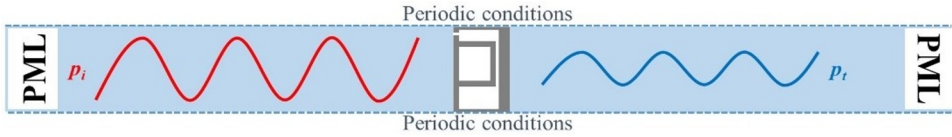


Fig. 2. Numerical model used for the calculation of the sound transmission.

Subsequently, we conduct a rigorous calculation of the transmission properties by applying a plane wave under periodic conditions. This process involves employing the numerical model illustrated in Figure 2 and solving Eq. 1 and Eq. 2 to accurately predict the transmission behavior of the unit cell. The sound transmission is calculated based on the equation as follows:

$$Transmission (dB) = 20 \times \log_{10}\left(\frac{p_t}{p_i}\right), \quad (5)$$

where p_i and p_t are the incident and transmitted pressures, respectively.

We get a thorough understanding of the unit cell's acoustic response through these incorporated analyses, opening the way for informed design choices and developments in acoustic metamaterials for enhanced noise control and insulation applications.

3 Results and discussion

Figure 3 presents the comprehensive results obtained from the study of the unit cell, offering a detailed insight into its acoustic behavior. In Figure 3(a), the dispersion curve is depicted, showcasing the relationship between frequency and wave vector within the first irreducible Brillouin zone. Concurrently, Figure 3(b) showcases the transmission responses, revealing how the unit cell interacts with incident sound waves under periodic conditions. Remarkably, both studies exhibit a remarkable level of agreement, affirming the accuracy of our numerical model and the validity of our findings. The interaction of dual Helmholtz resonators in the unit cell, each with its own volume, results in a transmission curve with asymmetric resonance and antiresonance peaks that are close to each other, allowing the production of a broad band gap with a significant acoustic dampening effect. Notably, the dispersion curve and transmission response jointly illustrate the presence of this significant band gap in the frequency range from 1 kHz to 3 kHz, taking the form of a distinct 'W' shape. This fascinating discovery holds substantial implications for acoustic insulation applications, as it allows for precise control over sound propagation and offers a pathway towards designing highly effective noise-cancellation devices and lightweight acoustic metamaterials with targeted band gap properties.

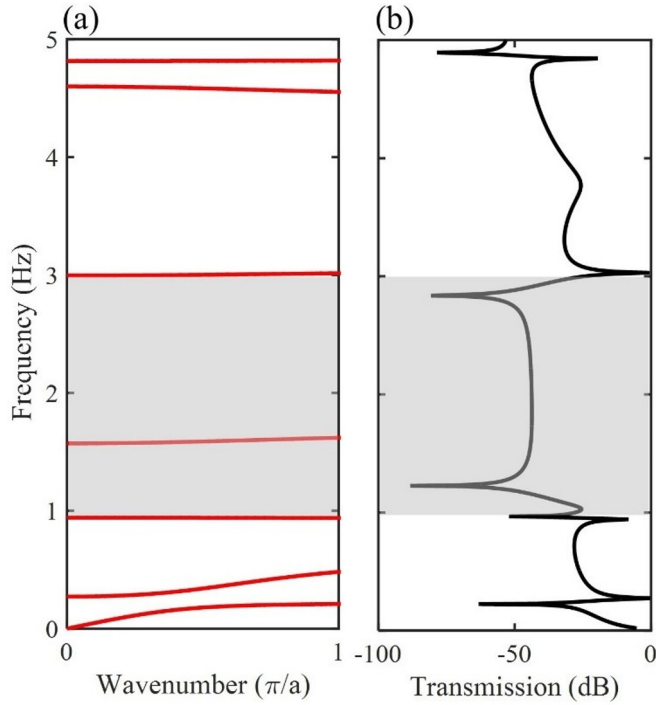


Fig. 3. Sound propagation responses. (a) The eigenfrequencies of the sound wave in function of the reduced wave number k are represented by the dispersion curve in the first Brillouin zone (ΓX). (b) The transmission response in decibels as a function of frequency.

Figure 4 presents an insightful parametric study examining the variation of the unit cell scale and its impact on the acoustic behavior of the panel metamaterial. Upon close examination, it becomes evident that as the scale increases, the width of the band gaps reduces, leading to their localization at lower frequencies. This observation is of great significance as it allows for fine-tuning the band gap properties to suit specific noise control requirements. Additionally, the study reveals an important parameter related to the diffraction limit. For unit cell scales of three or four, a diffraction phenomenon emerges in the high-frequency range. This diffraction effect imposes limitations on the operative frequency range and becomes particularly relevant when designing acoustic metamaterials for practical applications.

Overall, the parametric study results show that increasing the scale of the unit cell causes the appearance of band gaps, particularly in the lower frequency area. As a result, this provides useful insights for optimizing metamaterial design to achieve efficient sound insulation at lower frequencies, which are generally the most difficult to reduce. Furthermore, the observed diffraction phenomenon at different scales emphasizes the significance of carefully assessing the operative frequency range when using such metamaterials in real-world applications.

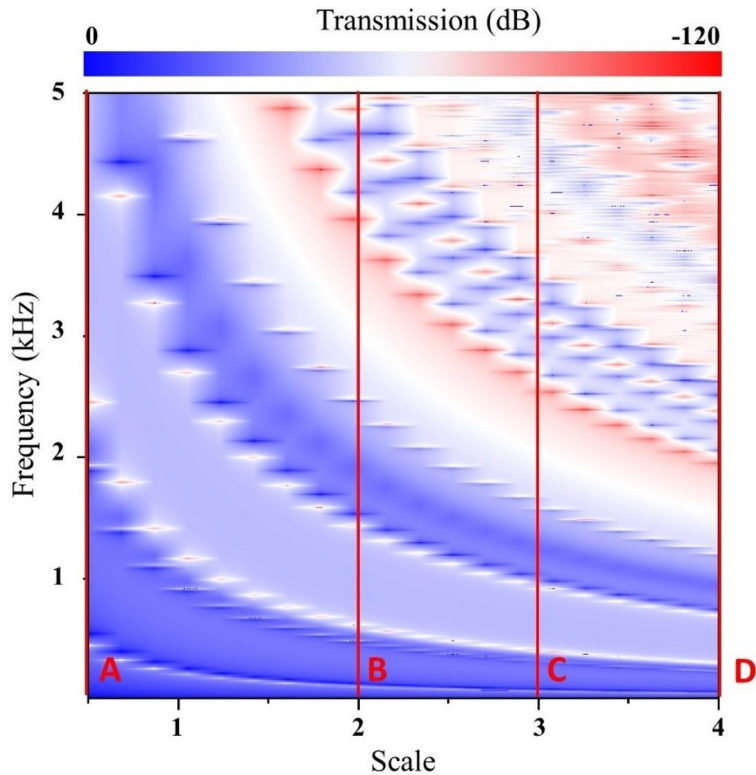


Fig. 3. A parametric examination of sound transmission as a function of frequency at various unit cell scales.

Figure 5 complements the parametric study by illustrating the transmission responses along four lines denoted as A, B, C, and D, while employing the mass law. The mass law serves as a fundamental principle for understanding and comparing the behavior of acoustic metamaterials. It establishes a relationship between the transmission properties of the material and its mass, providing valuable insights into the overall acoustic performance of the unit cell at different frequencies.

The transmission responses of lines A, B, C, and D offer a comprehensive view of the unit cell's acoustic behavior across a wide frequency range. This analysis demonstrates how the structure interacts with incident sound waves and provides essential information for evaluating the effectiveness of the metamaterial in attenuating specific frequency components. Furthermore, by using the mass law, we can gain knowledge about the connection between the mass of the unit cell and its transmission response, allowing us to optimize the metamaterial's properties to achieve the desired sound insulation capabilities. For example, on a scale of $3 \times a$, the first band gap begins at 300 Hz and ends at 1000 Hz, with a filling factor of 44% when compared to the mass law. For the scale $4 \times a$, the width of the band gap decreases and ranges from 100 Hz to 700 Hz, implying that any noise wave in these frequencies that interacts with these structures cannot be transmitted; in other words, these panels act as a barrier to trap sound waves in low frequencies.

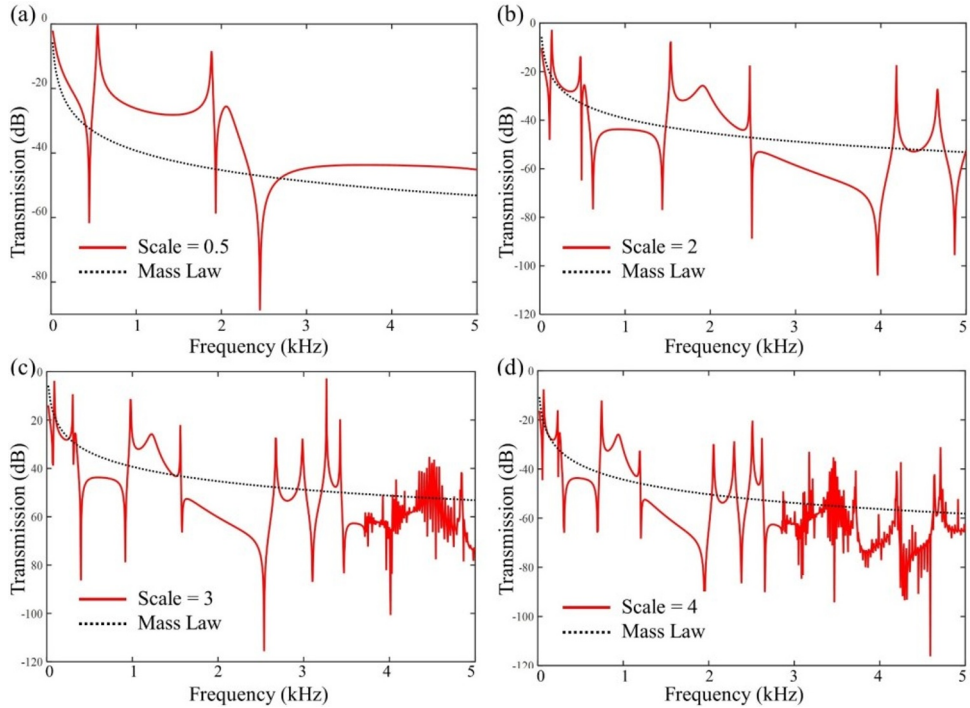


Fig. 3. The transmission responses at various unit cell scales compared with mass law. (a) The periodicity is represented by the scale $0.5 \times a$. (b) The periodicity is represented by the scale $2 \times a$. (c) The periodicity is represented by the scale $3 \times a$. (d) The periodicity is represented by the scale $4 \times a$.

Besides, the parametric study depicted in Figure 4 sheds light on the crucial role of unit cell scale in shaping the acoustic behavior of the metamaterial. It highlights the potential to tailor band gap properties by varying the scale and reveals the diffraction limit as a critical factor influencing the operative frequency range. Furthermore, Figure 5 enhances our understanding of the metamaterial's transmission characteristics by illustrating its response to incident sound waves along various lines while considering the mass law. These combined findings offer valuable guidance for designing highly efficient and targeted acoustic insulation solutions, paving the way for the development of lightweight acoustic metamaterials capable of significantly improving noise control across diverse applications and industries.

4 Conclusion

In conclusion, this study on lightweight acoustic metamaterial panels has yielded valuable insights into the design of innovative structures aimed at low-frequency sound insulation. The novel design, utilizing coupled Helmholtz resonators, has proven effective in creating a band gap with a distinctive 'W' shape, enabling precise control over sound propagation in specific frequency ranges. These low-frequency band gaps hold immense promise for noise control applications, offering an efficient means of reducing sound transmission and attenuating undesirable noise sources. Furthermore, the proposed design's versatility allows for the construction of a "rainbow trapping" effect by employing different unit cells with varying dimensions, each operating in distinct frequency ranges. This rainbow trapping capability opens up new possibilities for tailoring acoustic metamaterials to address specific noise challenges across a broad spectrum of frequencies. Overall, the findings from this study

offer valuable contributions to the field of acoustic engineering, providing a solid foundation for the development of lightweight panels and high-performance acoustic metamaterials.

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